PROCEEDINGS, TOUGH Symposium 2012
Lawrence Berkeley National Laboratory, Berkeley, California, September 17-19, 2012

ENHANCED HEAT TRANSPORT VIA SIMMERING PHENOMENA IN GEOTHERMAL MODELS

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ABSTRACT

Simmering, or enhanced heat transport via transient vapor bubbles is a persistent state in strongly heated H_2O systems, e.g., in household cooking. Although rarely discussed in geologic settings, simmering should be equally important and persistent in nature. Numerical models are used here to assess simmering in magma-hydrothermal systems using the latest NIST-standard high-temperature/pressure equation of state for H_2O, embedded in the TOUGH2 geothermal simulator. A HYDROTHERM model of the same setting was made for comparison. The TOUGH2 models exhibit persistent simmering, owing to the development of a strong feedback between heat transport rate, fluid pressure, and phase state. In freely convecting systems, this feedback is manifested in upflow zones by oscillatory P-T conditions, creating spiral paths along and to the liquid-stable side of the two-phase boundary, extending to supercritical conditions at depth. P-T vary cyclically at each point in the upflow zone by about ten degrees and tens of bars over a scale of decades as steam “bubbles” develop and buoyantly rise. This simmering develops whenever basal heating in the reservoir significantly exceeds liquid convective heat transport rates. Simmering enhances heat transport by an order of magnitude or more and successfully dissipates the excess heating. This state persists through almost all of prograde heating and much of retrograde cooling, even through external perturbations such as lithocap fracturing or magma re-intrusion.

HYDROTHERM models of an identical system do not exhibit simmering, and instead develop a longer-lived higher-saturation steam zone immediately above the magmatic heat source. Temperatures above this zone are significantly cooler than in the TOUGH2 models. TOUGH2 computational effort is much greater, as time steps decline to month scales when pressure spikes related to steam formation impact cell mass balances. The origin of this marked difference in result between the two codes most likely relates to differences in computation or treatment of fluid-property extrema. These extrema result in highly efficient heat transport (simmering) in TOUGH2, encouraging development of a vertically extensive simmering zone above the pluton. The extrema are not as influential in HYDROTHERM, limiting the vertical extent of boiling. This difference is at least partly related to the mathematical form of the equations of state (EOS), where the NIST EOS is physically based, and the HYDROTHERM EOS is a polynomial fit to tabulated values; however, regardless of EOS formulation, models with boundary inflow held on the two-phase boundary or its supercritical extension can exhibit simmering behavior.

INTRODUCTION

Incipient boiling (simmering) reflects the development of enhanced heat transport through transient phase change. Anyone who has boiled water has experience with this phenomenon; some of the earliest technical investigations of simmering arose from the nuclear power industry (Davis and Anderson, 1966; Tachibana et al., 1968; Takashi and Hirohisa, 1964). More recent research has focused on development of high-flux heat sinks for microcircuitry, utilizing two-phase phenomena to maximize heat dissipation on a microscopic scale (Qu and Mudawar, 2002, 2004). Given the ubiquity of incipient boiling in daily life, it is surprising that simmering is not a more common feature of hydrothermal/geothermal models. Indeed, abundant geological evidence exists for transient, cyclical convection, e.g., fine-scale hydrothermal banded veins and breccia, (Corbett and Leach, 1997), multidecadal variability of hot springs (Minerva Hot Springs, USNPS, 2012), and pre- and post-development seismicity at geothermal systems (Fialko and Simons, 2000). While these geological features are often attributed to tectonic fracturing or boiling events, the models outlined below demonstrate that periodic hydrothermal features can also be related to flow instability controlled by fluid properties, i.e., simmering. Similar flow instability has been observed and modeled for single-phase supercritical flow—black smoker systems, HYDROTHERM, Coumou et al. (2006); Fontaine and Wilcock (2007); Ingebritsen et al. (2010)—and two-phase subcritical two-phase flow (micro-channel heat sinks with "severe pressure drop oscillation"; Qu and Mudawar, 2003). Oscillatory boiling has also been modeled for a geyser conduit (Ingebritsen and Rojstaczer, 1996, *HYDROTHERM*) assuming extremely high permeability, with inlet conditions fixed on the two-phase boundary. In each of these cases, fluid properties control conditions in the convective outflow zone, and this is the key to development of simmering phenomena.

BACKGROUND

For simplicity, an idealized system was modeled approximating a single plutonic intrusion into uniform host rock with a previously-formed cap rock above the pluton (Figure 1). This is Example 10 of HYDROTHERM (Hayba and Ingebritsen, 1997; Kipp et al., 2008) with cap r ock added. Assigned rock properties are summarized in Table 1.

Results are compared for two hydrothermal simulators, HYDROTHERM (v. 3.1) and TOUGH2 (utilizing supercritical equation of state EOS1sc, Brikowski, 2001b). The fluid equation of state for *HYDROTHERM* uses bicubic interpolation of water properties tabulated in the NIST steam tables. The equation of state EOS1sc implements the physically based water-property computation routines available from NIST (1999). Compared to table lookup, EOS1sc is computationally intensive, but provides important increased accuracy in regions of water property extrema.

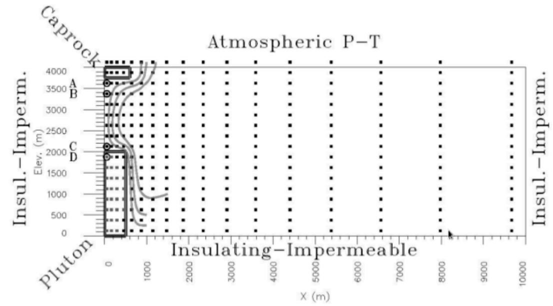

Figure 1. Computational grid and lithologic zones for hypothetical system of caprock, host rock and pluton. Cell centers shown by square symbols, permeability zone boundaries by gray rectangles. Streamlines for 5,000 years shown. Labels A-D show location of monitoring points for P-T profiles (Figure 3-Figure 4) along first column of nodes (at x = 50 m).

Table 1: Rock properties assigned to materials in Figure 1. Pluton permeability is temperature dependent, and increases below 400ºC. All units assigned thermal conductivity 2 W/mºC and heat capacity 1000 J/kgºC. Pluton initially at 900ºC.

Parameter	Cap rock	Host	Pluton
Porosity	0.05	0.1	0.05
Permeability(m^2)	10^{-18}	10^{-15}	10^{-18}

Transport Property Extrema

The effects of fluid-property extrema in hydrothermal systems have been observed in many numerical models (Brikowski, 2001a; Brikowski and Norton, 1989; Fontaine and Wilcock, 2007; Norton and Knight, 1977; Norton and Dutrow, 2001). The extrema provide a feedback mechanism by maximizing buoyancy forces (primarily dependent on horizontal density gradients, which are in turn dependent on fluid expansivity and compressibility) in a region of minimal viscosity (resistance to flow) and maximum heat capacity along the two-phase boundary and critical isochore (Figure 2). Since this feedback operates primarily on the convection rate, it is most visible in the upflow zones where those rates are highest.

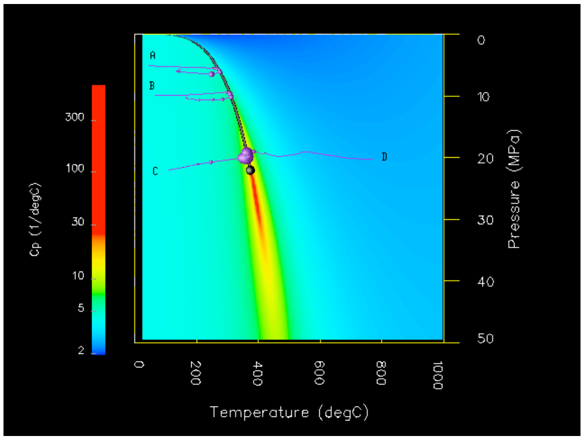

Figure 2. P-T vs. time paths (lines marked with spheres) in the upflow zone of a magma-hydrothermal system (point locations shown in Figure 1), TOUGH2-EOS1sc model. Letters show starting point of each path, points above pluton follow counter-clockwise paths, point "D" lies within pluton, and follows right-to-left path. Velocity magnitude (spheres, size proportional to magnitude) reaches a strong maximum in the vicinity of the two-phase boundary (gray line) and critical isochore (diamond). Shading shows zone of strong fluid property controls, represented here by Cp.

The nature of this feedback process can be illustrated by noting the evolution of fluid/rock P-T conditions and convection rates at fixed points in a magma-hydrothermal system model. Immediately after magma intrusion in such a system (Figure 1), conditions in the heated host rock migrate toward the two-phase boundary or critical isochore from low temperature (points A-C, Figure 2). As conditions enter high-density gradient zones along the two-phase boundary or critical isochore, increasing buoyancy forces cause a sharp increase in velocity (convection). This limits further temperature increase by increasing convective heat removal. Points in the hot pluton cool toward the critical isochore (e.g., point D, Figure 2), with velocity peaking sharply near the isochore, partly because of fluid property extrema, partly because of cooling-related fracture formation (brittle-ductile boundary is crossed).

Portions of the system attempting to depart from this zone of maximum density gradient experience reduced convection. Above the pluton, points depressurizing above the two-phase boundary don't heat as rapidly, and move left on the P-T diagram back into the region of maximum buoyancy. Similarly, pluton points cooling beyond the critical isochore experience reduced convection, and cool more slowly, eventually moving to the right on the P-T diagram back into the region of maximum convection along the critical isochore. Forced convection systems (externally controlled vertical pressure gradient) may show other P-T distributions, but upflow zones in freely convecting systems will strongly tend toward the two-phase boundary/critical isochore, and exhibit boiling-curve P-T profiles (e.g., Figure 4).

RESULTS

Both the TOUGH2 and HYDROTHERM model results are strongly influenced by fluid property extrema. Both experience rapid conductive heat transfer from the pluton into adjacent country rock, forming vigorous early upflow zones at its lateral margin (X=0.8-1 km, Figure 1). Early in both models, boiling begins directly above the pluton at elevation 2 km. In the HYDROTHERM model, this zone persists to about 3000 yrs, reaching up to 35% steam. It then disappears, reappearing during 7000–8000 yrs (i.e., only small depth ranges lie on the two phase boundary—Figure 3). In contrast, the TOUGH2 model develops a vertically extensive incipient boiling zone by 3000 yrs, persisting until around 8000 yrs (Figure 4). In this zone, small regions of minimal steam saturation form at its deeper end, and advect upward, accumulating beneath the lithocap (Figure 7). Pressure spikes related to the formation or condensation of steam affect cell mass balance, and reduce timesteps to less than one year. Individual cells in the simmering zone follow elliptical paths in P-T space, slowly warming during the prograde development of circulation, then cooling (Figure 6). Each transition to two-phase causes a significant pressure spike, and thereby an increase in local heat transfer (Figure 8). It is this phenomenon that is key to modern microchannel heat sinks, and likely drives more efficient hydrothermal heat transport than is generally recognized.

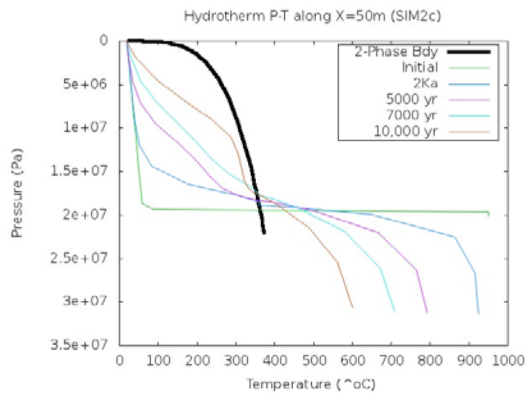

Figure 3. *HYDROTHERM* P vs. T along X=50 m

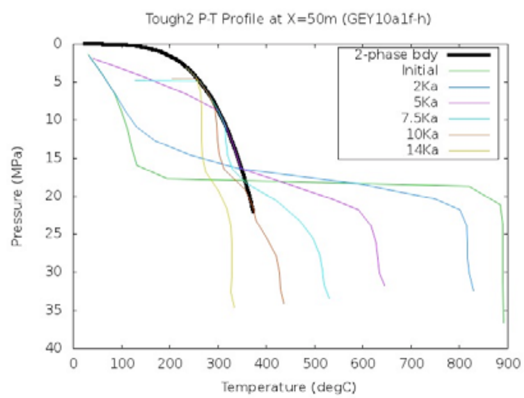

Figure 4. TOUGH2 P vs. T along X=50 m

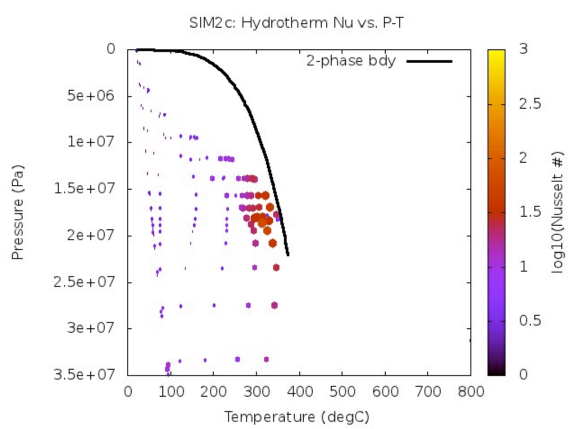

Figure 5. *HYDROTHERM* Nusselt number vs. P-T, 5Ka. An extensive simmering zone (Figure 5) will develop only with extreme permeability (e.g., $k = 10^{-8}$ m^2; Ingebritsen and Rojstaczer, 1996).

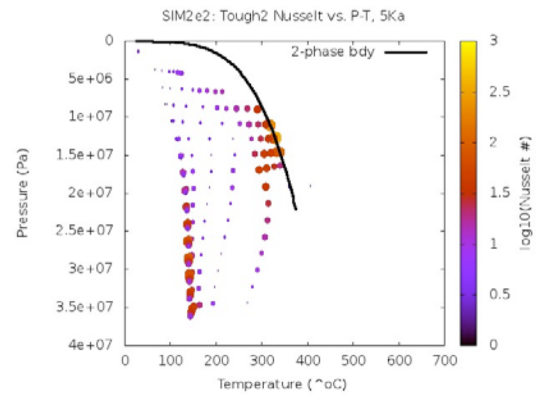

Figure 5. TOUGH2 Nusselt number vs. P-T, 5Ka. Elevated Nu points at lower left represent inflow into convective cell

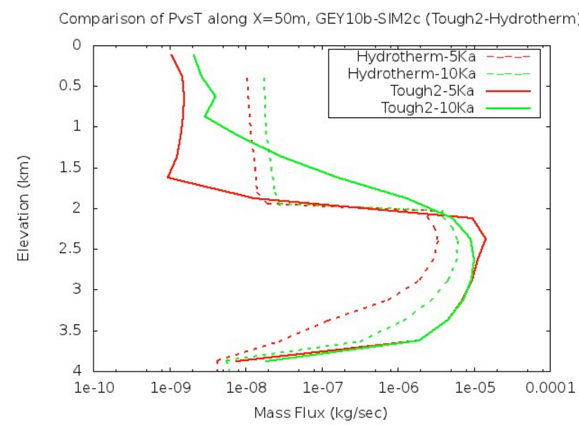

Figure 7. Comparative Mass Flux along X=50 m

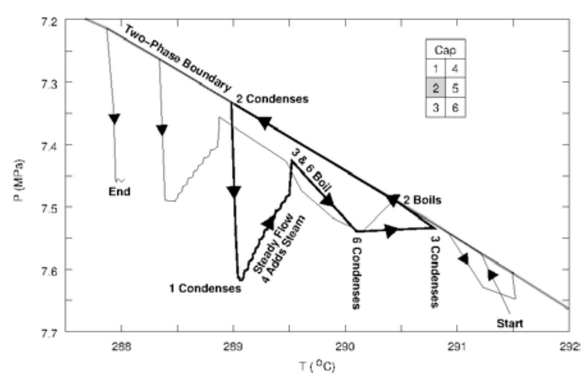

Figure 6. TOUGH2 oscillatory P-T path at point B (Figure 1) for 50 years, labeled as point 2 in this diagram (see inset), at approximately 7000 years in the simulation. Oscillatory P-T conditions produced by advecting steam phase, yielding roughly elliptical counter-clockwise path on P-T diagram. One complete cycle is illustrated by bold line, prior and following cycles shown by thin line. Two-phase boundary shown by gray line.

The effect of fluid transport property extrema is clearest when considering cell Nusselt number (Nu, ratio of convective to conductive heat flow) plotted on a P-T diagram (Figure -Figure 5). Points lying along the two-phase boundary (in the upflow region above the pluton) experience maximum buoyancy forces and heat capacity. This significantly raises Nu, to a much greater extent in TOUGH2 (max. Nu ~400) vs. HYDROTHERM (max Nu ~120), despite similar above-pluton mass fluxes for both models (Figure). The heat-transport feedback represented by this enhanced Nu serves to reinforce the simmering region. Whether driven by differences in formulation of EOS, or averaging of phase properties, relative or thermal permeability formulations, fluid paths move off the two-phase boundary in HYDROTHERM compared to TOUGH2, and computed heat transport is not as efficient. As a result, heating of country rock above the pluton is significantly greater in the TOUGH2 model of this system (compare curves, Figure 3–Figure 4). Interestingly, this produces considerably greater steam saturations immediately above the pluton in the HYDROTHERM model, and lesser but more persistent steam in the TOUGH2 model. Ultimate heat transport from the magma is limited by its conductive rind, so the duration of hydrothermal circulation is similar in both models.

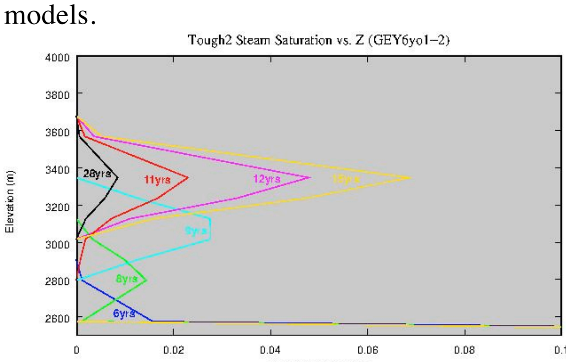

Figure 7. TOUGH2 steam saturation profiles x=50 for sequential times. Shown are years after beginning of the cycle at 5390 system years. The low-density steam phase forms at base of two-phase zone, then migrates upward buoyantly.

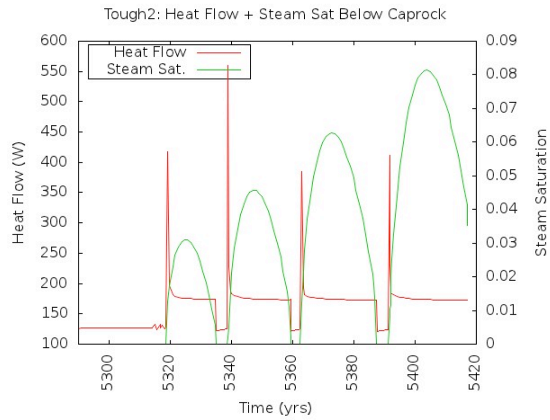

Figure 8. TOUGH2 heat flux and steam saturation vs. time at point "A", Figure 1. See text for detailed explanation. The vertical development of the last cycle in this figure (5375-5425 yrs) is shown in Figure 7.

CONCLUSIONS

Incipient boiling or simmering is a ubiquitous phenomenon in rapidly heated systems, and many of us observe it almost daily. It seems quite reasonable that simmering is common in hydrothermal systems as well, and abundant geological evidence exists for short-term transient thermal behavior in paleo- and modern hydrothermal/geothermal systems. If simmering is common in natural systems, it should also be common in models of those systems, yet it is rarely reported. Since simmering inherently represents a feedback system of enhanced heat transport, it is likely to be most apparent when great attention is paid to accuracy of EOS and heat-transfer formulations. The most accurate will be physically based EOS formulations, but these can be extremely computation intensive. For models concerned with detailed conditions above a heat source, e.g., for prograde geothermal systems or detailed alteration studies, simmering is likely to be a dominant heat transport process.

ACKNOWLEDGMENTS

The original modeling in this study was supported by U. S. Dept. of Energy grant DE-FG07-98ID13677.

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